Energy Efficiency of White LEDs

The energy efficiency of light-emitting diodes (LEDs) is expected to rival the most efficient white light sources by 2010. But how energy efficient are LEDs right now? This fact sheet discusses various aspects of lighting energy efficiency and the rapidly evolving status of white LEDs.

Luminous Efficacy

Energy efficiency of light sources is typically measured in lumens per watt (lm/W), meaning the amount of light produced for each watt of electricity consumed. This is known as luminous efficacy. DOE's long-term research and development goal calls for white-light LEDs producing 160 lm/W in cost-effective, market-ready systems by 2025. In the meantime, how does the luminous efficacy of today's white LEDs compare to traditional light sources? Currently, the best white LEDs approach the efficacy of compact fluorescent lamps (CFLs). However, there are several important caveats, as explained below.

Color Quality

To date, LED luminous efficacy similar to that of CFLs has been achievable only with higher color temperature products, which produce a "cool" or bluish-toned light and relatively low color rendering index (CRI) in the 70s. LEDs with warmer color appearance and higher CRI are only marginally more efficacious than incandescent sources. However, this is changing rapidly, with new performance improvements being announced regularly by the industry. For more detail, see DOE fact sheet "Color Quality of White LEDs."

System Efficacy

Fluorescent and high-intensity discharge (HID) light sources cannot function without a ballast, which provides a starting voltage and limits electrical current to the lamp. LEDs also require supplementary electronics, usually called drivers. The driver converts line power to the appropriate voltage (typically between 2 and 4 volts DC for high-brightness LEDs) and current (generally 200-1000 milliamps or mA), and may also include dimming and/or color correction controls.

Because the LED and driver operate as a system, driver "losses" should be accounted for in estimating LED efficacy. Currently available LED drivers are typically about 85% efficient. So LED efficacy should be discounted by 15% to account for the driver. For a rough comparison, the range of system (lamp and ballast or LED and driver) efficacies for traditional and LED sources are shown below.

Light Source	Typical System Efficacy Range in lm/W (varies depending on wattage and lamp type)
Incandescent	10-18
Halogen incandescent	15-20
Compact fluorescent (CFL)	35-60
Linear fluorescent	50-100
Metal halide	50-90
White LED 5000K	25-43*
White LED 3300K	17-34*

*Current as of June 2006.

Thermal Effects

The luminous flux figures cited by LED manufacturers are based on an LED junction temperature (T_j) of 25°Celsius. LEDs are tested during manufacturing under conditions that differ from actual operation in a fixture or system. In general, luminous flux is measured under instantaneous operation (perhaps a 20 millisecond pulse) in open air. T_j will always be higher when operated under constant current in a fixture or system. Well-designed systems with adequate heat sinking will maintain T_j well below the manufacturer's rated maximum temperature (typically around 125°C but some as high as 185°C). To ensure lumen maintenance over the expected life, T_j should be kept below about 90°C. Check manufacturer data sheets for temperature specifications.

Terms

Lumen – the SI unit of luminous flux. The total amount of light emitted by a light source, without regard to directionality, is given in lumens.

Luminous efficacy – the total luminous flux emitted by the light source divided by the lamp wattage; expressed in lumens per watt (lm/W).

System efficacy – the total luminous flux emitted by the light source divided by the total power input to the system, including power used by the driver or ballast; expressed in lm/W.

Application efficiency – While there is no standard definition of application efficiency, we use the term here to denote an important design consideration: that the desired illuminance level and lighting quality for a given application should be acheived with the lowest practicable energy input. Light source directionality and intensity may result in higher application efficiency even though luminous efficacy is lower relative to other light sources.

Efficiency or efficacy? – The term "efficacy" normally is used where the input and output units differ. For example in lighting, we are concerned with the amount of light (in lumens) produced by a certain amount of electricity (in watts). The term "efficiency" usually is dimensionless. For example, lighting fixture efficiency is the ratio of the total lumens exiting the fixture to the total lumens produced by the light source. "Efficiency" is also used to discuss the broader concept of using resources efficiently.

Comparing LEDs to Traditional Light Sources

Energy efficiency proponents are accustomed to comparing light sources on the basis of luminous efficacy. To compare LED sources to CFLs, for example, the most basic analysis should compare lamp-ballast efficacy to LED+driver efficacy in lumens per watt. Data sheets for white LEDs from the leading manufacturers will generally provide "typical" luminous flux in lumens, test current (mA), forward voltage (V), and junction temperature (T_j), usually 25 degrees Celsius. To calculate lm/W, divide lumens by current times voltage. As an example, assume a device with typical flux of 45 lumens, operated at 350 mA and voltage of 3.42 V. The luminous efficacy of the LED source would be:

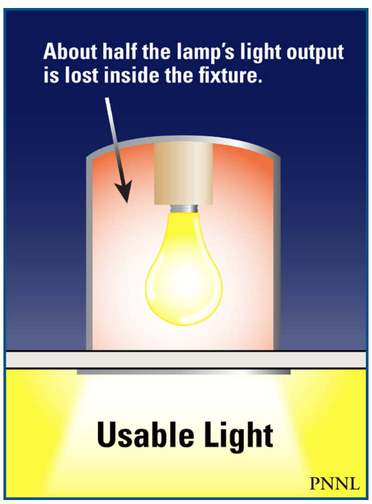
$$45 \text{ lumens}/(.35 \text{ amps} \times 3.42 \text{ volts}) = 38 \text{ lm/W}$$

To include typical driver losses, multiply this figure by 85%, resulting in 32 lm/W. Because LED light output is sensitive to temperature, some manufacturers recommend de-rating luminous flux by 10% to account for thermal effects. In this example, accounting for this thermal factor would result in a system efficacy of approximately 29 lm/W. However, thermal tolerance is one of the many areas in which LED performance continues to improve, so this recommendation may change. For lighting applications requiring a directed light source, such as task lighting, application efficiency should also be considered (see below).

Application Efficiency

Luminous efficacy is an important indicator of energy efficiency, but it doesn't tell the whole story, particularly with regard to directional light sources.

Due to the directional nature of their light emission, LEDs potentially have higher application efficiency than other light sources in certain lighting applications. Fluorescent and standard "bulb" shaped incandescent lamps emit light in all directions. Much of the light produced by the lamp is lost within the fixture, reabsorbed by the lamp, or escapes from the fixture in a direction that is not useful for the intended application. For many fixture types, including recessed downlights, troffers, and under-cabinet fixtures, it is not uncommon for 40-50% of the total light output of the lamp(s) to be lost before it exits the fixture.



*Cut-away view of recessed downlight installed in ceiling

LEDs emit light in a specific direction, reducing the need for reflectors and diffusers that can trap light, so well-designed fixtures and systems using LEDs can potentially deliver light more efficiently to the intended location.

For example, several manufacturers have introduced LED systems for lighting refrigerated display cases in grocery stores. These products are currently based on white LEDs with lower luminous efficacy than the fluorescent lamps they are designed to replace. But because the system design takes advantage of the directional nature of LEDs and their especially good performance under low temperatures, they are demonstrating energy savings of 50% or more compared to standard fluorescent case lights.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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